Probing Core-collapse Supernova Physics with Neutrinos

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AstroParticule et Cosmologie (APC)

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Outline

1. Motivation
   - Multi-messenger approach → neutrinos
2. Core-collapse Supernova Neutrinos
   - Emission, Propagation and Detection
3. Future Galactic Supernova
   - Location and shock wave tracking
4. Summary

Outline

Motivation: SN physics not well understood

Core-collapse supernovae impressive astrophysical events

- huge luminosity ($L^{\nu}_{\rm SN} \sim 10^{20} L_{\odot}$)
- feed the galaxies with heavy elements
- progenitors of the long soft gamma-ray bursts (GRBs)
- accelerator of cosmic rays, ...

but not yet completely understood

- explosion mechanism
  - delayed neutrino-driven [Buras *et al.*, 2006, Bruenn *et al.*, 2006, Marek and Janka, 2007]
  - magnetic-rotational (MHD) [Ostriker and Gunn, 1971, Leblanc and Wilson, 1970, Akiyama *et al*, 2003]
  - acoustic [Burrows, Livne, Dessart, Ott, and Murphy, 2006 and 2007]
- r-process nucleosynthesis, ...

⟶ what to do?

Motivation: multi-messenger astronomy required

a) improve simulations: 3D, multi-energy ν transport, GR, ...

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    - information on: progenitor, circumstellar matter, acceleration of CRs, ...

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- Gravitational Waves: emitted from the inner layers →
  - conditions in the inner regions → core
  - explosion mechanisms

[E. Müller *et al.*, 2004 , Ott, 2009, K. Kotake *et al.*, 2009]

Motivation: multi-messenger astronomy required

[Ott, 2009]

GW Emission Process	Potential Explosion Mechanism		
	MHD Mechanism (rapid rotation)	Neutrino Mechanism (slow/no rotation)	Acoustic Mechanism (slow/no rotation)
Rotating Collapse and Bounce	**strong**	none/weak	none/weak
3D Rotational Instabilities	**strong**	none	none
Convection & SASI	none/weak	weak	weak
PNS g-modes	none/weak	none/weak	**strong**

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  - only nearby SNe observable ($d \lesssim 100$ kpc)

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- Neutrinos $\longrightarrow$ why?

Motivation: Neutrinos ideal messengers

a) nice properties $\rightarrow$ ideal messengers

- neutral $\rightarrow$ point back to the source
- very weakly interacting $\sigma(\gamma + e) \sim 10^{19}\sigma(\nu + e) \Rightarrow$
  - escape from deep regions in stars
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b) copiously created in SNe

- SN core: low energy (MeV) neutrinos drive the deleptonization and cooling towards the NS
- outer shells: protons accelerated in the shocks collide with the gas → π, K → high energy ($\gtrsim$ TeV) neutrinos [V. Berezinsky and Ptuskin, 1988, E. Waxman and A. Loeb, 2001]

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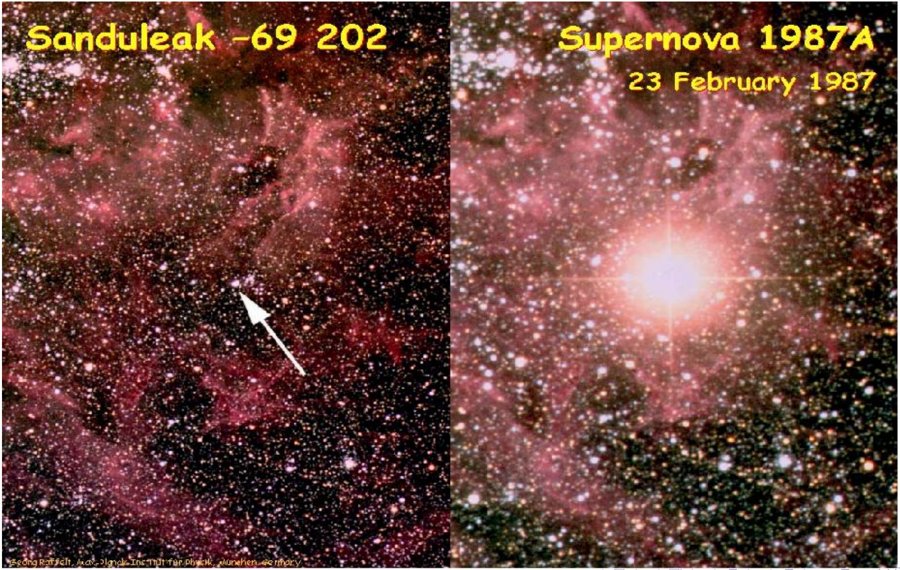
Motivation



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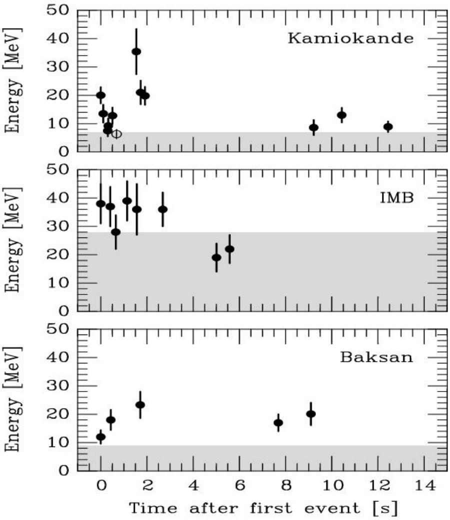
Kamiokande
IMB
Baksan
Energy [MeV]
Energy [MeV]
Energy [MeV]
0
10
20
30
40
50
0 2 4 6 8 10 12 14
Time after first event [s]

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Neutrino Emission

Energy balance

Gravitational binding energy $\sim \frac{G_N M^2}{R} \sim O(10^{53})$ erg

- $\sim$ 0.01 % optical energy
- $\sim$ 1 % kinetic energy
- $\sim$ 99 % carried away by neutrinos
  - all flavors : $\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$
  - roughly equipartitioned

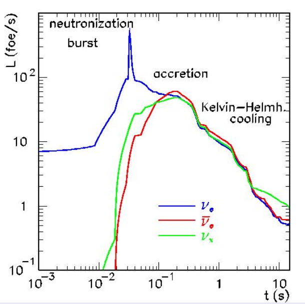
Neutrino Emission

Energy balance

Energy balance: $O(10^{53})$ erg in all ν flavors

Duration

several seconds



[Totani, Sato, Dalhed and Wilson, 1998]

Neutrino Emission

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Duration

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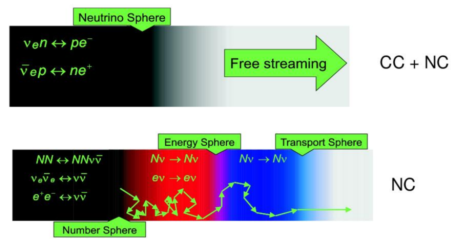
Spectra

Formation



[Keil, Raffelt and Janka, 2003]

Neutrino Emission

Energy balance

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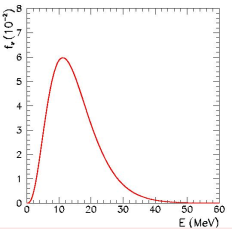
Spectra

Parametrization

$$F^0_\nu(E) \propto \left(\frac{E}{\langle E\rangle}\right)^\alpha e^{-(\alpha+1)E/\langle E\rangle}$$

- $\langle E\rangle \approx 10 - 20$ MeV
- pinching factor $\alpha \approx 2 - 5$



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Spectra

Spectra: $F^0_\nu(E, \alpha, \langle E \rangle) \rightarrow$ uncertainties in α and $\langle E \rangle$

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Duration: several seconds

Spectra

Spectra: $F^0_\nu(E, \alpha, \langle E \rangle) \rightarrow$ uncertainties in α and $\langle E \rangle$

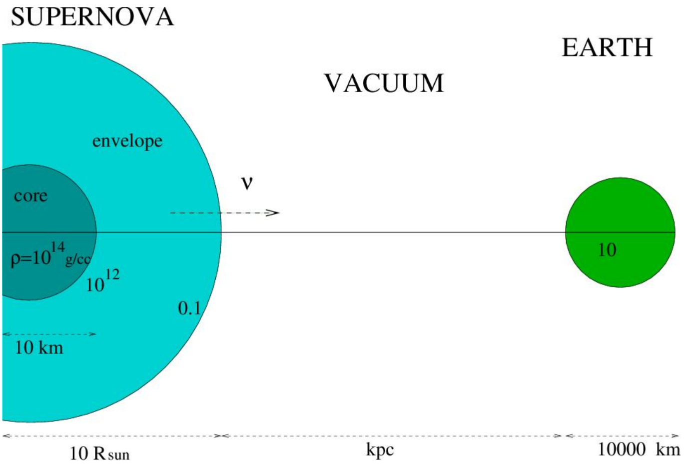
but

Proto neutron star composition $\Rightarrow$ differences in the spectra

(hierarchy: $\langle E_{\nu_e} \rangle \lesssim \langle E_{\bar{\nu}_e} \rangle \lesssim \langle E_{\nu_x} \rangle$)

$\Rightarrow \nu$ conversion $\rightarrow$ observable effects

Neutrino Propagation



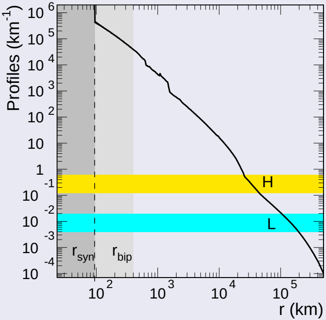
Neutrino Propagation

Schrödinger equation

$$i\frac{d}{dr}\begin{pmatrix}\nu_\alpha \\ \bar{\nu}_\alpha\end{pmatrix} = [H_{\text{kin}} + H_{\text{weak}}(r) + H_{\nu\nu}(r)]_{\alpha\beta}\begin{pmatrix}\nu_\beta \\ \bar{\nu}_\beta\end{pmatrix}$$

Possible neutrino flavor conversion in:

- bipolar region : $H_{\nu\nu}(r_{\text{bip}}) \approx H_{\text{kin}}$
- resonances: $H_{\text{weak}}(r_{\text{res}}) \approx H_{\text{kin}}$
  - High densities (H): $\rho(r_{\text{H}}) \sim 10^3$ g/cm^3
  - Low densities (L): $\rho(r_{\text{L}}) \sim 10$ g/cm^3



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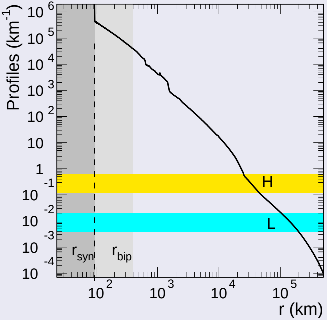
Possible neutrino flavor conversion in:

- bipolar region : $H_{\nu\nu}(r_{\rm bip}) \approx H_{\rm kin}$
- resonances: $H_{\rm weak}(r_{\rm res}) \approx H_{\rm kin}$
  - High densities (H): $\rho(r_{\rm H}) \sim 10^3$ g/cm^3
  - Low densities (L): $\rho(r_{\rm L}) \sim 10$ g/cm^3

depending on

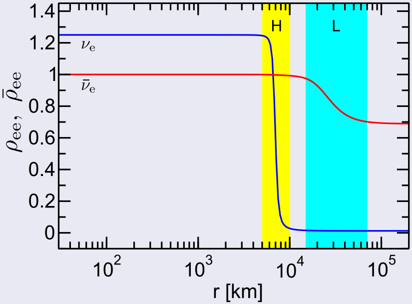
- ν properties: θ_{ij}, mass hierarchy
- medium: ν fluxes, matter profiles



Neutrino Propagation

if ν background not important [Andreu Esteban-Pretel *et al.*, 2007, 2008]

Normal ν mass hierarchy (NH)



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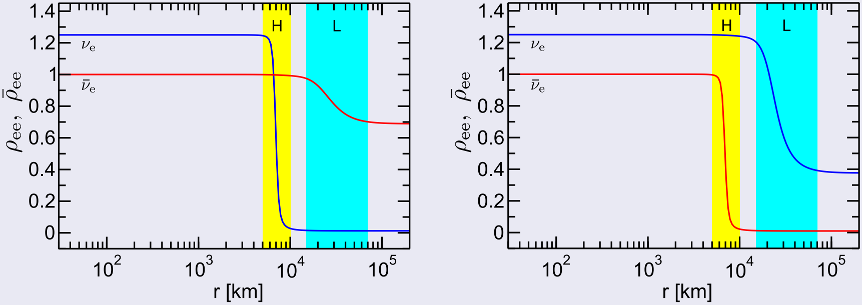
Normal ν mass hierarchy (NH)

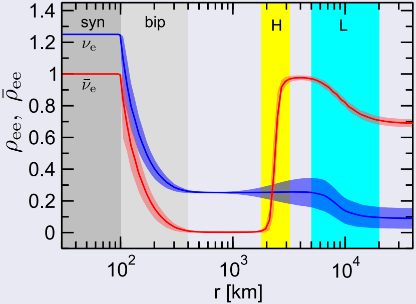
Inverted ν mass hierarchy (IH)



Neutrino Propagation

with ν bkgnd	without ν bkgrnd

Inverted ν mass hierarchy (NH)



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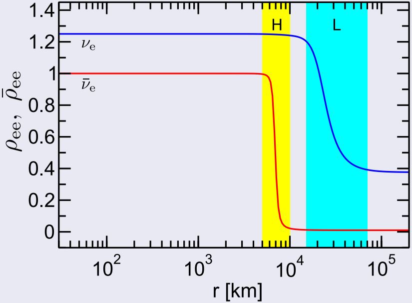

Neutrino Propagation

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Inverted ν mass hierarchy
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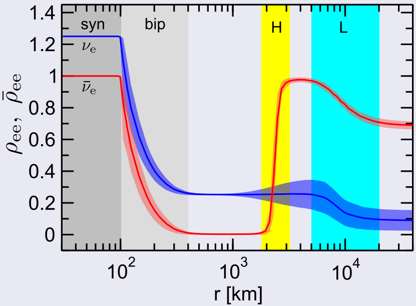

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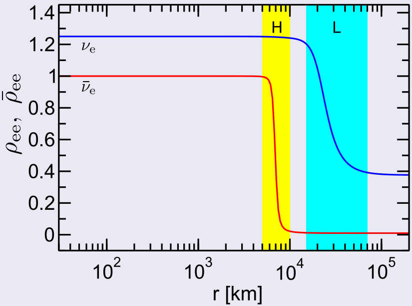


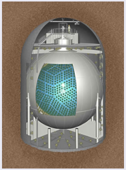
ν flavor $\longrightarrow$ essential for detection

Neutrino Detection

Low-energy ν (MeV)

Cherenkov (Super-Kamiokande), scintillator (Borexino, KamLand), liquid Ar

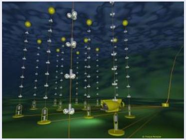
- $\bar{\nu}_e + p \rightarrow n + e^+$ (10000 at 10 kpc)
- $\nu + e \rightarrow \nu + e$ (300 at 10 kpc)
- $\nu_e + {}^{16}O \rightarrow X + e^-$ (500 at 10 kpc)



High-energy neutrinos ($\gtrsim$ 1 TeV)

Neutrino Telescopes (Antares, IceCube), Extensive Air Showers (AGASA, PAO), Nitrogen Fluorescence (HiRes, PAO)

- muon tracks: ν_μ
- showers: ν_α
- double bang: ν_τ



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What could we learn from a future galactic SN?

ν properties

- mass scale
- mass hierarchy
- θ_{13}
- μ_ν
- NSI
- ν decay
- sterile

arguments

- time of flight delay
- spectral distortion
- energy loss
- nucleosynthesis
- neutronization burst
- angular dependence
- diffuse SN ν backg.

SN physics

- location
- distance
- explosion mechanism
- cosmic star formation rate
- black hole formation

Location: SN pointing with $\nu e \rightarrow \nu e$

Motivation: MeV-ν burst precedes optical $\rightarrow$ Early Warning

- early light observation
- warning for noisier ν detectors (Antares, Icecube, ...)
- gravitational waves detectors

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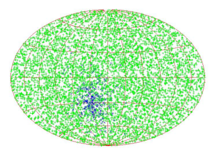
- gravitational waves detectors

Methods

- Low energy: MeV-burst [A. Burrows *et al.*, 1992, J. F. Beacom and P. Vogel, 1999, S. Ando and K. Sato, 2002]
  - triangulation $\delta \cos\theta \simeq 0.5$
  - asymmetric reactions
    - $* \; \bar{\nu}_e p \to n e^+$
      - e^+ slight asymmetry : $\delta \cos\theta \simeq 0.2$
      - n systematic dislocation (scint.)
    - $* \; \nu e \to \nu e$ forward peaked : $\delta\theta \lesssim 8^\circ$ (SK)
      - $+$ Gd (n tagging) $\to \; \lesssim 3^\circ$
- High energy (TeV): km^2 high-energy ν telescope $\delta\theta \sim O(0.1^\circ)$

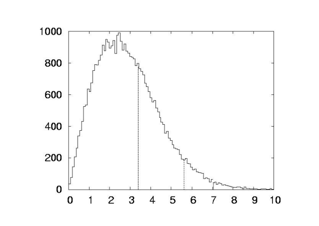
Location: SN pointing with $\nu e \rightarrow \nu e$

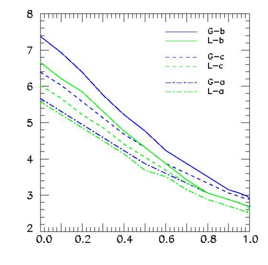
Detector: SK-like



- reactions
$$\begin{cases} \bar{\nu}_e + p \rightarrow n + e^+ & (7000 - 11500) \\ \nu + e \rightarrow \nu + e & (250 - 300) \\ \nu_e + {}^{16}O \rightarrow X + e^- & (150 - 800) \end{cases}$$

- angular resolution: Landau distribution $\epsilon_{\rm tag}=0 \rightarrow \ell_{95} \simeq 8^\circ$ $\epsilon_{\rm tag}=1 \rightarrow \ell_{95} \simeq 3^\circ$

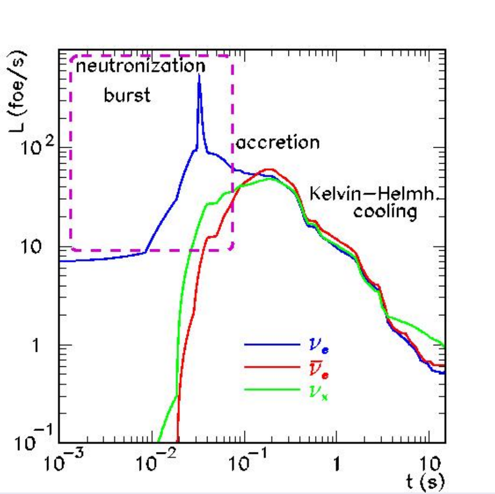




[R. T, Semikoz, Raffelt, Kachelrieß, and Dighe, 2003]

Location: SN distance with the ν_e burst

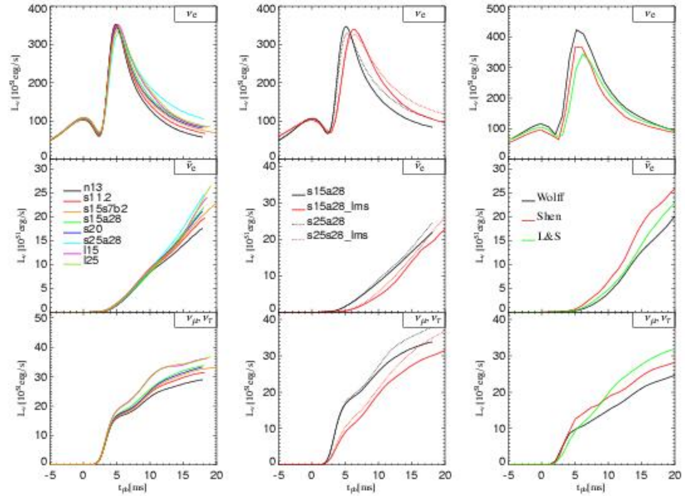
shock wave reaches ν-sphere $\Rightarrow$ intense and short ($\sim$ 20 ms) ν_e emission



Location: SN distance with the ν_e burst

robust feature ⇒ standard candle

[Kachelrieß, R. T, Buras, Janka, Marek and Rampp, 2005]



Location: SN distance with the ν_e burst

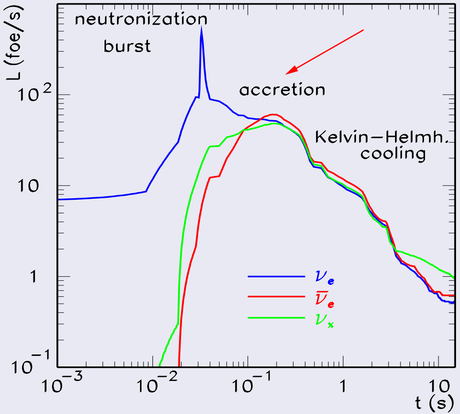
- why? powerful if SN lightcurve is obscured by dust
- is it feasible? $\Delta t \approx 30$ ms $\Rightarrow$ Megaton water Cherenkov (or big liquid Ar)

$$\Downarrow$$

Result: Megaton detector + SN at 10 kpc $\Rightarrow \sim 10$ %

[Kachelrieß, R. T, Buras, Janka, Marek and Rampp, 2005]

Progenitor properties with accretion/cooling



Progenitor properties with accretion/cooling

accretion and cooling phase:

↓

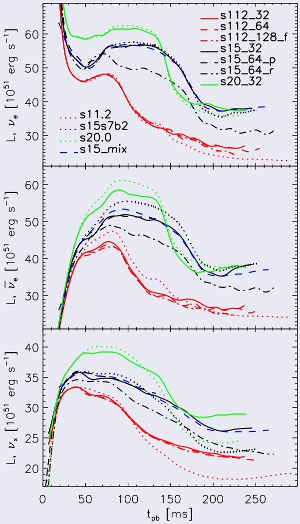
ν flux depends on the progenitor properties: mass, rotation, ...

⇓

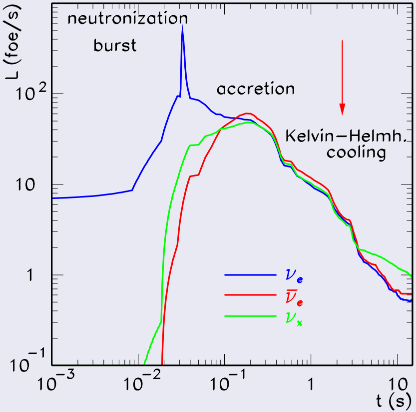
ν-flavor flux determination

⇓

progenitor characterization



Shock wave propagation during cooling

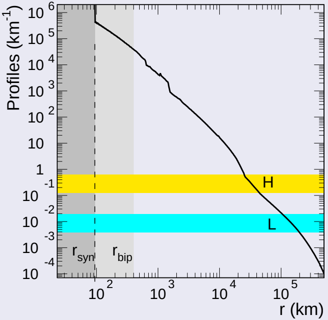


Shock wave propagation during cooling

- ν propagation depends on the medium conditions
- shock wave passage strongly modifies the medium

$$\Downarrow$$

ν propagation affected



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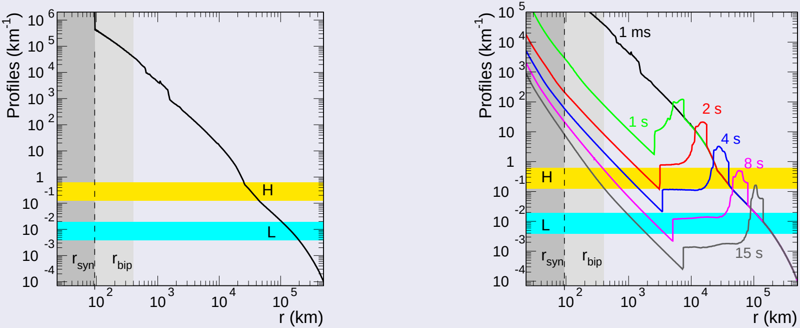

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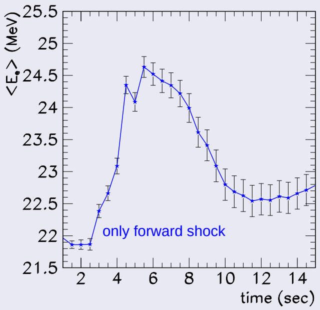

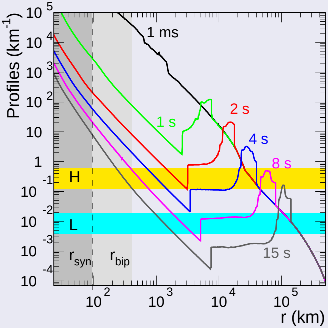

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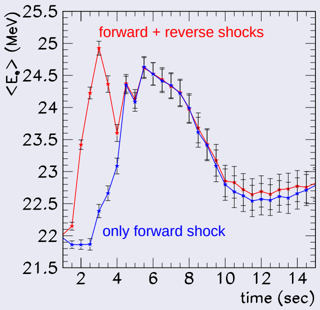

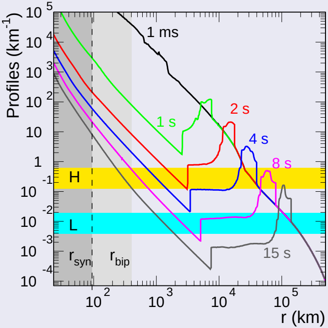

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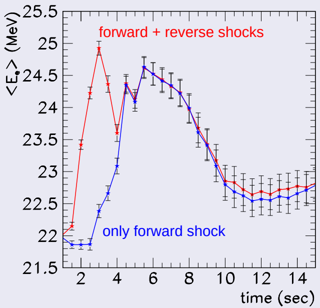

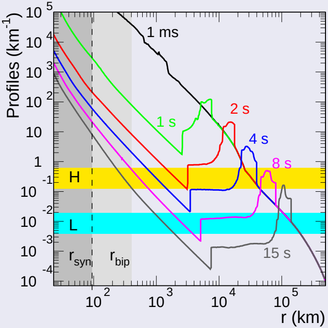

ν flavor conversion $\Longrightarrow$ shock wave tracking

Summary

SN understanding $\rightarrow$ multi-messenger astronomy $\rightarrow$ ν's

- Ideal messengers
  - neutral particles $\Rightarrow$ point back the source
  - weakly interacting $\Rightarrow$ escape from the inner layers
  - flavor conversion $\Rightarrow$ sensitive to the medium properties
- copiously produced in SN
  - TeV neutrinos in the outer shells
  - MeV neutrinos in the core

$$\Downarrow$$

galactic SN + water Cherenkov detector:

- pointing $\begin{cases} -\ \text{MeV} - \nu \rightarrow 3^\circ \ldots 8^\circ \rightarrow \text{early warning} \\ -\ \text{TeV} - \nu \rightarrow O(0.1^\circ) + \text{hint for acceleration mechanism} \end{cases}$
- distance: robustness of neutronization burst $\rightarrow$ $\sim$ 10% accuracy
- SN explosion tomography: matter effects on ν oscillations

Summary

That's future → in the meanwhile ...

- diffuse SN ν flux (and nearby SNe) [Ando, Beacom, Lunardini, Sato, ...]

$\downarrow$

constrain rate → SNe, and might be NS binaries and dark GRBs??

Summary

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- a bit of patience: rate 1 every 30 years and the last one in 1987 ...

T. Totani, K. Sato, H. E. Dalhed and J. R. Wilson,
"Future detection of supernova neutrino burst and explosion mechanism,"
Astrophys. J. **496** (1998) 216

M. T. Keil, G. G. Raffelt and H. -Th. Janka,
"Monte Carlo study of supernova neutrino spectra formation,"
Astrophys. J. **590** (2003) 971

C. Lunardini and A. Y. Smirnov,
"Probing the neutrino mass hierarchy and the 13-mixing with supernovae,"
JCAP **0306** (2003) 009

C. Lunardini and A. Y. Smirnov,
"Supernova neutrinos: Earth matter effects and neutrino mass spectrum,"
Nucl. Phys. B **616** (2001) 307

A. S. Dighe, M. T. Keil and G. G. Raffelt,
"Detecting the neutrino mass hierarchy with a supernova at IceCube,"
JCAP **0306** (2003) 005

A. S. Dighe, M. T. Keil and G. G. Raffelt,

"Identifying earth matter effects on supernova neutrinos at a single detector,"
JCAP **0306** (2003) 006

A. S. Dighe, M. Kachelriess, G. G. Raffelt and R. Tomàs,
"Signatures of supernova neutrino oscillations in the earth mantle and core,"
JCAP **0401** (2004) 004

R. C. Schirato, G. M. Fuller, (. U. (. LANL), UCSD and LANL),
"Connection between supernova shocks, flavor transformation, and the neutrino signal,"
arXiv:astro-ph/0205390.

G. L. Fogli, E. Lisi, D. Montanino and A. Mirizzi,
"Analysis of energy- and time-dependence of supernova shock effects on neutrino crossing probabilities," Phys. Rev. D **68** (2003) 033005

R. Tomas, M. Kachelrieß, G. Raffelt, A. Dighe, H. T. Janka and L. Scheck,
"Neutrino signatures of supernova shock and reverse shock propagation,"
JCAP 0409 (2004) 015

G. L. Fogli, E. Lisi, A. Mirizzi and D. Montanino,

"Probing supernova shock waves and neutrino flavor transitions in next-generation water-Cherenkov detectors,"
arXiv:hep-ph/0412046.

V. Barger, P. Huber and D. Marfatia,
"Supernova neutrinos can tell us the neutrino mass hierarchy independently of flux models,"
arXiv:hep-ph/0501184.

M. Kachelriess, R. Tomas, R. Buras, H. T. Janka, A. Marek and M. Rampp,
"Exploiting the neutronization burst of a galactic supernova,"
Phys. Rev. D **71** (2005) 063003

S. Ando, J. F. Beacom and H. Yürkel
astro-ph/0503321

S. Ando and K. Sato,
"Relic neutrino background from cosmological supernovae,"
New J. Phys. **6** (2004) 170

L. E. Strigari, J. F. Beacom, T. P. Walker and P. Zhang,

"The concordance cosmic star formation rate: Implications from and for the supernova neutrino and gamma ray backgrounds,"
arXiv:astro-ph/0502150.

I. Gil-Botella *et al.*

E. Cappellaro, M. Turatto,
Invited review at the meeting: "The influence of binaries on stellar population studies", ed. D. Vanbeveren (Brussels 21-25 Aug. 2000), astro-ph/0012455.

W. Baade and F. Zwicky,
"On Supernovae", Proceedings of the National Academy of Science, **20**, 254-259 (1934).

S. A. Colgate and R. H. White,
Ap. J. **143**, 626.

S. A. Colgate and R. H. White,
Ap. J. **143**, 626.

H. Bethe and J. R. Wilson,
Ap. J. **295**, 14.

F. S. Kitaura, H. -Th. Janka and W. Hillebrandt,
"Explosions of O-Ne-Mg cores, the Crab supernova, and subluminous Type II-P supernovae", astro-ph/0512065.

A. Burrows, E. Livne, L. Dessart, C. D. Ott and J. Murphy,
"A new mechanism for core-collapse supernova explosions", astro-ph/0510687.

E. Akhmedov and ...

A. Esteban-Pretel, R. Tomàs and J. W. F. Valle,
"Probing non-standard neutrino interactions with supernova neutrinos," arXiv:0704.0032 [hep-ph].

J. M. Soares and L. Wolfenstein, "Neutrinos Masses And Lifetimes From Supernova Observations," Phys. Rev. D **40** (1989) 3666. L. M. Krauss, P. Romanelli and D. N. Schramm, "The Signal from a galactic supernova: Measuring the tau-neutrino mass," Nucl. Phys. B **380** (1992) 507. A. Burrows, D. Klein and R. Gandhi, "The Future of supernova neutrino detection," Phys. Rev. D **45** (1992) 3361. J. F. Beacom and P. Vogel, "Mass signature of supernova nu/mu and nu/tau neutrinos in

SuperKamiokande," Phys. Rev. D **58** (1998) 053010
[arXiv:hep-ph/9802424].

G. Raffelt, G. Sigl and L. Stodolsky, Phys. Rev. Lett. **70** (1993) 2363 [arXiv:hep-ph/9209276].

G. Raffelt and G. Sigl, Astropart. Phys. **1** (1993) 165 [arXiv:astro-ph/9209005].

J. Lesgourgues and S. Pastor, Phys. Rept. **429** (2006) 307 [arXiv:astro-ph/0603494].

R. Buras, H. T. Janka, M. Rampp and K. Kifonidis, arXiv:astro-ph/0512189.

Th. H. Janka and K. Kifonidis, private communication

G. L. Fogli, E. Lisi, A. Mirizzi and D. Montanino, JCAP **0606** (2006) 012 [arXiv:hep-ph/0603033].

A. Friedland and A. Gruzinov, arXiv:astro-ph/0607244.

- S. Pastor and G. Raffelt, Phys. Rev. Lett. **89** (2002) 191101 [arXiv:astro-ph/0207281].
- H. Duan, G. M. Fuller and Y. Z. Qian, Phys. Rev. D **74** (2006) 123004 [arXiv:astro-ph/0511275].
- H. Duan, G. M. Fuller, J. Carlson and Y. Z. Qian, Phys. Rev. D **74** (2006) 105014 [arXiv:astro-ph/0606616].
- H. Duan, G. M. Fuller, J. Carlson and Y. Z. Qian, Phys. Rev. Lett. **97** (2006) 241101 [arXiv:astro-ph/0608050].
- S. Hannestad, G. G. Raffelt, G. Sigl and Y. Y. Y. Wong, Phys. Rev. D **74** (2006) 105010 [arXiv:astro-ph/0608695].
- G. G. Raffelt and G. Sigl, Phys. Rev. D **75** (2007) 083002 [arXiv:hep-ph/0701182].
- H. Duan, G. M. Fuller, J. Carlson and Y. Z. Qian, Phys. Rev. D **75** (2007) 125005 [arXiv:astro-ph/0703776].
- G. G. Raffelt and A. Y. Smirnov, arXiv:0705.1830 [hep-ph].

- Andreu Esteban-Pretel, S. Pastor, R. Tomàs, G. G. Raffelt and G. Sigl, arXiv:0706.2637 [astro-ph].
- G. F. Fogli, E. Lisi, A. Marrone and A. Mirizzi in preparation.
- A. Esteban-Pretel, R. Tomàs and J. W. F. Valle, "Probing non-standard neutrino interactions with supernova neutrinos," arXiv:0704.0032 [hep-ph].
- H. Minakata, H. Nunokawa, R. Tomàs and J. W. Valle, "Probing supernova physics with neutrino oscillations," Phys. Lett. B **542** (2002) 239 [hep-ph/0112160].
- H. Minakata, H. Nunokawa, R. Tomàs and J. W. Valle, "Degeneracy," in preparation.
-
-
- M. Rampp and H. T. Janka, Astrophys. J. **539**, L33 (2000), astro-ph/0005438.
- A. Mezzacappa *et al.*,

Phys. Rev. Lett. **86**, 1935 (2001), astro-ph/0005366.

T. A. Thompson, A. Burrows, and P. A. Pinto,
Astrophys. J. **592**, 434 (2003), astro-ph/0211194.

M. Liebendoerfer *et al.*,
Phys. Rev. **D63**, 103004 (2001), astro-ph/0006418.

R. Tomàs, D. Semikoz, G. G. Raffelt, M. Kachelrieß and A. S. Dighe, "Supernova pointing with low- and high-energy neutrino detectors," Phys. Rev. D **68** (2003) 093013 [hep-ph/0307050].

M. Kachelrieß, A. Strumia, R. Tomàs and J. W. Valle,

K. Z. Stanek *et al.*, Astrophys. J. **591** (2003) L17 [arXiv:astro-ph/0304173].

H. T. Janka, K. Langanke, A. Marek, G. Martinez-Pinedo and B. Mueller, Phys. Rept. **442** (2007) 38 [arXiv:astro-ph/0612072].

R. Buras, M. Rampp, H. T. Janka and K. Kifonidis, Astron. Astrophys. **447** (2006) 1049 [arXiv:astro-ph/0507135].

C. D. Ott, Class. Quant. Grav. **26** (2009) 063001 [arXiv:0809.0695 [astro-ph]].

SNR RX J1713.7-3946 HESS Col.

E. Mueller, M. Rampp, R. Buras, H. T. Janka and D. H. Shoemaker,
"Towards gravitational wave signals from realistic core collapse supernova models," Astrophys. J. **603** (2004) 221 [arXiv:astro-ph/0309833].

A. Burrows, D. Klein and R. Gandhi,
"The Future of supernova neutrino detection,"
Phys. Rev. D **45** (1992) 3361.

J. F. Beacom and P. Vogel,
"Can a supernova be located by its neutrinos?,"
Phys. Rev. D **60** (1999) 033007.

S. Ando and K. Sato,
"Determining the supernova direction by its neutrinos,"
Prog. Theor. Phys. **107** (2002) 957.